THE CONSIDERATION OF OPTIMAL CONTROL ALGORITHMS FOR HYBRID RENEWABLE ENERGY SYSTEMS

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Sadržaj – Hibridni energetski sistemi predstavljaju pouzdanija rešenja od onih koja se oslanjaju samo na elektro-energetsku mrežu. U okviru ovih sistema najčešće se nalaze obnovljivi izvori energije poput foto-ćelija, vetro turbina i baterija. U ovom radu, analizirani su arhitektura kao i optimalni kontrolni algoritmi implementriani u okviru simulatora jednog takvog sistema. Pri tome, osnovni parametri na kojim je baziran simulator jesu energetska efikasnosti i isplativost celokupnog sistema. Takođe, predstavljena su i dva simulaciona scenarija i tri karakteristične konfiguracije sistema. Dalja analiza je sprovedena uz pomoć realnih vrednosti parametara pojedinih energetskih modula, vodeći ka predloženoj strategiji na kojoj je zasnovan glavni kontroler u sistemu. Prototip simulatora, u svom trenutnom stanju, je razvijen na MATLAB/Simulink platformi.

Abstract – *Hybrid renewable energy systems are usually more reliable than systems that rely on a grid only. The system configuration, commonly used in practical applications, is photovoltaic (PV)-Wind-Battery-Grid. In this paper, the optimal control algorithms for simulation of such systems were analyzed in terms of energy-efficiency and cost-benefit characteristics. The analysis was performed utilizing the typical values of alternative sources and batteries parameters. Furthermore, two possible simulation scenarios related to three characteristic system configurations were proposed as well. The prototype simulator in its current state is based on the MATLAB/Simulink platform. Finally, the control strategy and optimization of controller for a given hybrid system is proposed.*

1. INTRODUCTION

Renewable energy is any source of energy that can be used without depleting its reserves. Therefore, utilization of those resources is imperative. They include solar energy, wind, wave, biomass and hydro energy. However, energy sourcing decisions for new and existing buildings are far from optimal as the factors affecting them in terms of producing, storing, and using energy, are becoming more complex. In the context of this paper, "energy sourcing" includes a design decision as to what energy infrastructure should be deployed, either at the design or the retrofit stage. More important, “energy sourcing” implies a real time, “dynamic decision” controlling the balance between energy supply, storage, use and feed-to-the-network.

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Energy Warden aims at assessing the RET (Renewable Energy Technology) potential of a building based on the meteorological data, pricing information, building characteristics and energy consumption patterns. Main products of Energy Warden Project are Energy Warden Simulator (EW – S) and Energy Warden Controller (EW – C) and Energy Warden Policy (EW – P).

This paper discusses a prototype version of a professional simulation environment of energy modules (producing, storing, using), EW – S. It will serve for analysis and modeling of new and existing buildings that use RET and serve decision making on investments related to RET deployment in the building domain.

The expected strategic impact of such a simulator should consider carrying out a detailed cost benefit analysis and optimization of RET potential in any given building, while contributing the EU’s target for renewable energy which will be 20% share by 2020.

2. SIMULATOR USE SCENARIOS

Looking closer into perspectives of this simulator there is a necessity of two different time – frame use scenarios, since it should provide a cost benefit analysis as well as set points for EW – C needed for real – time control. Both of these scenarios will have same inputs as following. Meteorological data, electricity cost/pricing data, energy consumption patterns and building information, see Fig 1. Main difference between imported data is resolution which is going to be used.

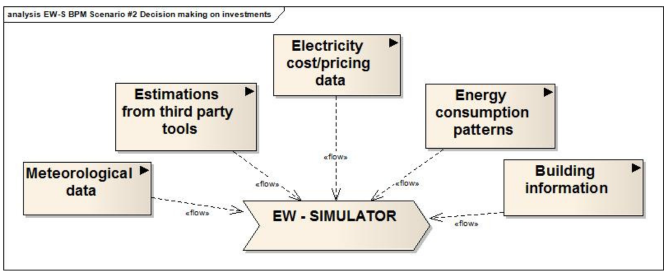

Figure 1 Simulator interfaces

Meteorological data can be obtained on hourly basis for almost any country in the world. It consists of external air temperature, global solar radiation at a horizontal plane, local or meteorological wind speed, wind direction, and other parameters.

Regarding consumption patterns, there are intraday and intraweek seasonal patterns. They largely depend on a specific type of building, but the basic consumption patterns consider residential, business, industrial and institutional buildings. Energy consumption also depends on a building geometry and construction, and can be obtained via third-party software [1].

A. Long time – frame scenario

The long time – frame scenario presents simulator as a standalone application serving decision support on investments related to RET deployment in the building domain. In this scenario our client should provide a request for design/redesign of planned/existing infrastructure which will serve as input for the simulation used for creating a report on optimal energy infrastructure.

Meteorological data and energy consumption patterns are used on an annual time – frame basis. They consist of average, minimum and maximum values for a whole year or even longer period.

As a result of this use scenario, our client will receive a report on selection and size of production and storage units. Selection implies not only to nominal characteristics but also commercially available units with these characteristics. However, variety in meteorological and energy consumption data apply not only to selecting size and model of storage and production units, but may also suggest slightly different suggested architecture.

Iterative procedure for selecting the wind turbine size and the number of PV panels needed for a system to meet a specific load from is described in [2]:

1. Select commercially available unit sizes for wind turbine, PV panel and storage battery.
2. Since the rating for the wind turbine far exceeds that of a single PV panel, keep the number of turbines (Kw) constant and increase the number of PV panels (Ks) until the system is balanced, i. e. the curve of difference between generation and load for the system has an average of zero over a given period of time.
3. Repeat step 2 for different number of wind turbines, ie. Kw=0,1,2,3,… as needed.
4. Calculate the total system annual cost for each combination of Kw and Ks that satisfies the requirements in step 2.
5. Choose the system with the lowest cost.

Important characteristic of renewable systems is break – even point, which presents time within money assigned to renewable energy units and systems is reversed to consumer via little electricity bill. When calculating overall costs of RET employed, one should also consider a lifetime of production and storage. For example, a battery have a lifetime of about 1500 cycles, which is lifetime expectancy of 4 years, while PV and wind turbines have lifetime expectancy of around 20 years [2].

A. Short time – frame scenario

Short time – frame simulation will provide decision support for EW – C. This will be achieved through a range of set points calculated for a specific infrastructure in the client's premises.

When a customer decides about overall system architecture and particular energy units, more precise simulation of that system is needed. Short time – frame simulation is going to provide integration with EW – C and deliver accurate predictions on available energy resources.

That will be possible using 4 – days forecast data on hourly basis. However, forecast errors can occur, and for overcoming this problem, simulator will also be connected to sensor networks in order to be aware of hardware currently operating conditions at particular location. The forecast error processing of the energy management could be alternatively tackled by increasing production and storage capacity.

3. PROTOTYPE SYSTEM ARCHITECTURE

The whole system, which consists of energy infrastructure, has to be modeled in order to provide accurate predictions on energy flows. In order to do that, possible solutions for system architecture are presented.

Three types of energy units should be found inside the system starting from energy production modules and energy storage models to energy use modules. Energy production units consist of wind turbine, both AC and DC, and photovoltaic. Energy storage units include batteries, while consumption units regard consumer devices. This classification should not be considered very strictly, since storage units perform as energy production units as well. Apart from conventional energy consumers, an excess of energy can be transferred towards electrical grid. Specialized controller will provide real-time control of whole infrastructure. It can be implemented using fuzzy logic or neural networks approach.

As proposed in [3], there are multiple types of electrical circuit architecture that could be used depending on client needs and site capabilities, depicted in Fig. 2. In the first architecture (a), the generators and the battery are all installed in one place and are connected to a main AC bus bar before being connected to the grid. This system is centralized in the sense that the power delivered by all the energy conversion systems and the battery is fed to the grid through a single point. In this case, the power produced by the PV system and the battery is inverted into AC before being connected to the main AC bus. The energy conversion systems can also be connected to the grid in a decentralized manner as shown in the figure (b). The power sources in this architecture do not need to be installed close to each other as in (a), and they do not need to be connected to one main bus bar. The power produced by each source is conditioned separately to be identical with the form required by the grid. The third architecture utilizes a main centralized DC bus bar (c). So, the energy conversion systems that produce AC power, namely the wind energy converter and the diesel generator, first deliver their power to rectifiers to be converted into DC before it is being delivered to the main DC bus bar. A main inverter takes the responsibility of feeding the AC grid from this main DC bus.

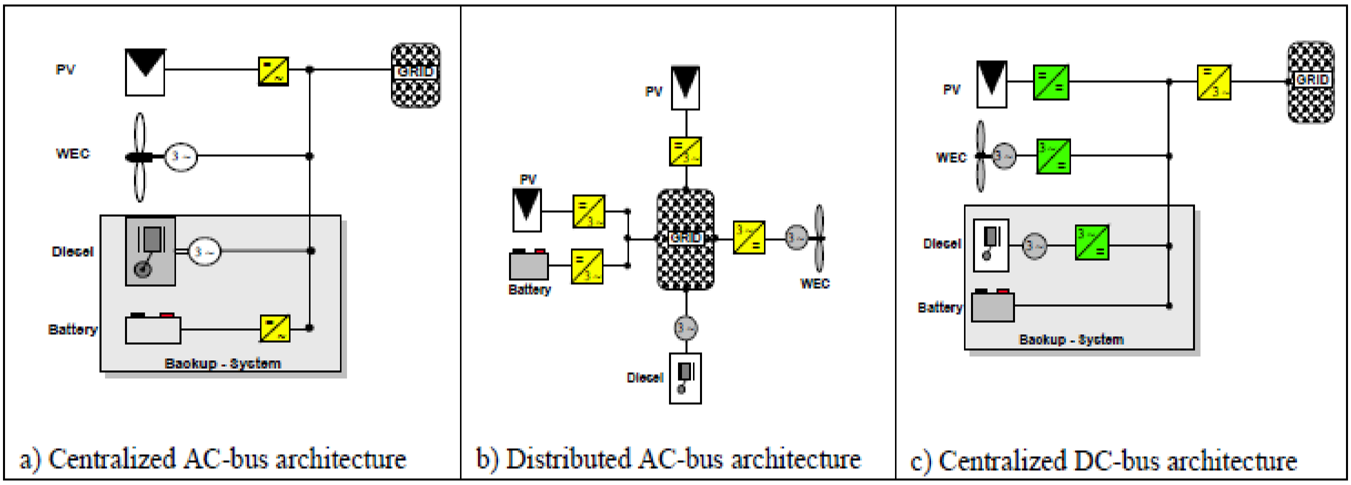

Figure 2 Three types of electrical circuit architecture

The architecture given in the Fig. 3 proposed in [4] is the one upon which the simulator will be based. It is combination of the centralized AC-bus and DC-bus architecture shown in the Fig. 1(a) and 1(c) but without diesel generator. The AC side contains all the AC power sources and loads, while the DC side contains all the DC power sources, loads and the storage. Addition of another bus provides more efficient utilization of energy, since there are no double conversions. Each bus includes subsystems associated with each of the power generators and storage devices, such as wind turbines, photovoltaic panels and batteries. Each subsystem has built-in controller which main purpose is to operate a device in appropriate manner. Apart from controlling a device, it also has the responsibility to communicate with master controller, providing data from measurements. This data is used for implementing overall controlling algorithm.

The power system also includes power converters that are not included in any subsystem. Converters connect the two buses and are components independent of the storage subsystem or either bus. The power converters include rectifiers, inverters, bi-directional converters, rotary converters, maximum power point trackers, dump loads, and synchronous condensers. These elements involve certain amount of lost energy.

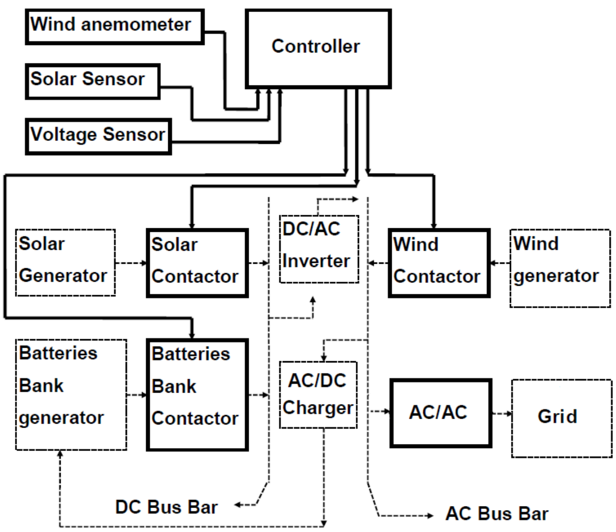

Figure 3 The prototype system architecture

4. PARAMETERIZATION OF ENERGY PRODUCTION UNITS

The main aim is to develop a prototype version of a professional simulation environment of energy and managing modules which could be easily parameterized, see Fig 4.

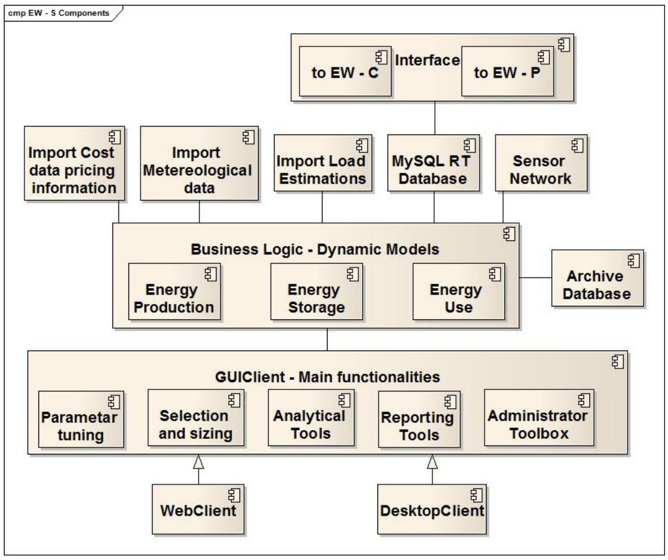

Figure 4 Component model

The simulator will be implemented in MATLAB/Simulink. Energy units will be developed as blocks and subsystems, using elements from Simulink library or developing custom functions. Controller block will also be simulated for presenting decision logic.

There are some limitations when using a MATLAB® Simulink® model concerning the web interface for EW – S, since the long time – frame simulation will be web-based application. A Simulink Report Generator is able to produce web view of a model for web deployment. The web view consists only of set of images wrapped in a html document, and does not offer parameter input and actual simulation running. Therefore, input parameters are provided using html form, while actual simulation is running on a server machine.

Result of simulation, containing both figures and data, is going to be presented as new html page, see Fig 5.

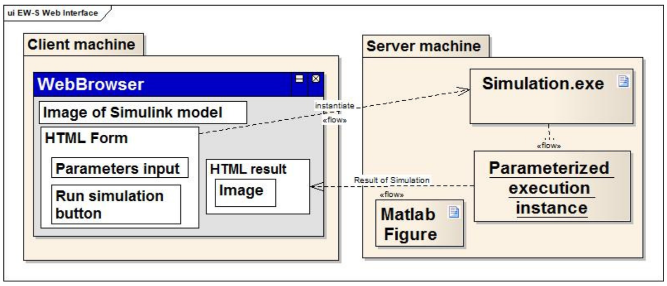

Figure 5 Web interface

Preliminary remarks on development of energy production and storage units are given according to [5].

A. Parameters of photovoltaic

Insolation data is converted into power output from the PV array using the following variables:

$$P_{PV}(t) = f(Ins(t), T(t), A, E_{ff_{pv}}) \qquad (1)$$

where Ins(t) is the insolation data at time t (kW/m^2), A is the area of a single PV panel (m^2), and Eff_{pv} is the overall efficiency of the PV panels and the DC/DC converter. Eq. (1) will assume that the PV array has a tracking system and a maximum power point tracker.

However, this model does not contain wind speed chilling effect or converter delay effects. These simplifications have minimal effect on the simulation of the energy management system using hourly level averaged production quantities. Overall parameters of commercial PV module are listed in Table 1.

PV panel parameters	
Maximum power (W)	120
Efficiency (%)	12
Area (m^2)	1.02
Annual maintenance cost ($)	0
Total capital cost ($)	614

Table 1

B. Parameters of wind turbine

Average hourly wind speed data is evaluated and converted to wind turbine power. If the speed is between the cut-in and the rated speed of the wind turbine, then the power output is defined as:

$$P_{Wind}(t) = f(\rho, A, v(t), C_p, Eff_{AD}) \qquad (2)$$

where ρ is the air density (kg/m^3), A is the swept area of the rotor (m^2), v is the wind speed (m/s), C_p is the efficiency of the wind turbine, and Eff_{AD} is the efficiency of the AC/DC converter (assumed to be 95% in this study).

Wind turbine parameters	
Rated output (kW)	1
Cut-in speed (m/s)	2.5
Rated speed (m/s)	11
Cut-out speed (m/s)	13
Rotor diameter (m)	2.5
Air density (kg/m3)	1.225
Total capital cost($)	3200
Annual maintenance cost($)	100

Table 2

Parameters of commercial wind turbine that are considered in this simulation are listed in the Table 2. Pitch angle, turbulence and extreme wind speed are not taken into account.

C. Parameters of battery

Battery will be modeled with power and voltage parameters as listed in Table 3. Apart from energy consumption patterns, battery dimensioning will be performed regarding loss of load probability (LOLP) factor, which presents power failure time period divided buy a given period of time. One more aspect, that should be carefully revised when dimensioning a battery, is the fact that batteries must not be discharged too deeply and for a long time in order to extend their lifetime [6].

Battery	
Voltage (V)	12
Capacity (kWh)	1.35
Roundtrip efficiency (%)	85
Minimum charge (%)	30
Capital cost ($)	130

Table 3

Apart from energy modules, the simulator will have modules for importing data, user interface, interface towards database and a module responsible for communication with EW – C. The nature of communication between EW – S and EW – C has great impact on development of the simulator. Since EW – C should manage energy flows inside a building in a real – time, there will not be enough resources to communicate directly with EW – S. Therefore, EW-C will occasionally collect information from real-time database when needed. EW-S will be also interfaced to EW-P, which presents higher level functionality that will support policy conformance, allowing monitoring building performance against existing policies and standards.

An archive database will also be available for storing the user profiles as well as overall communication between EW-Simulator and other modules.

5. CONTROLLER OPTIMIZATION IN HYBRID RENEWABLE ENERGY SYSTEMS

A. Control

A Controller will manage how energy is allocated between production, storage and use. It will take into account electricity market prices, forecasts for demand and renewable energy production. For controller optimization, an appropriate simulator will be developed. This simulator will provide a range of set points that will be used for initialization of controller.

Renewable energy sources are used most efficiently when they send energy directly to consumer devices. Grid will be used when renewable sources are insufficient, while surpluses of energy from renewable sources will be stored in battery, or when battery is full, sold to grid.

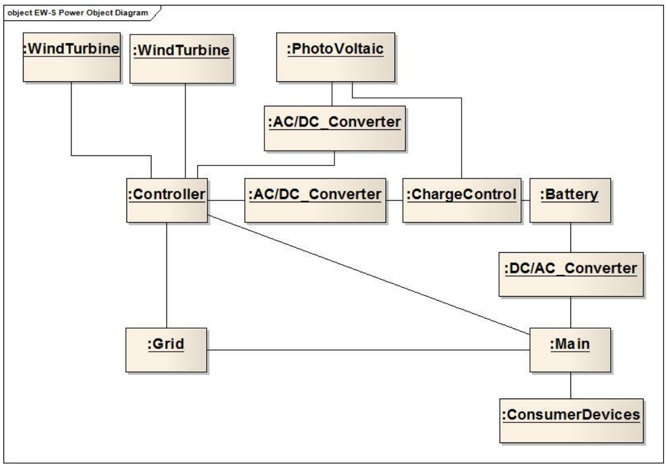

Figure 6 Energy flows diagram

The controller will manage overall energy flows in the system, see Fig 6. Since the main objective is to create a self sustainable building, in the most cases the battery is used for supplying additional energy. However, that leads to another important question which is: when to charge the battery from the grid? One important parameter of the battery is state of charge (SOC). Three characteristic cases are explained in [7]:

1. *Zero-charge battery*: the batteries are never charged using the grid. Therefore the set point of SOC is 0%. This is economically feasible approach, but autonomy does not exist.
2. *Full cycle-charge strategy*: the batteries are charged to 100% of their capacity from grid (SOC set point=100%). This approach offers the best autonomy but it has low efficiency, due to double conversion when selling to the grid and buying from it to fill the battery.
3. *Predictive control strategy* assumes SOC set point is between 0% and 100%. The battery will be charged via grid until it reaches certain SOC resulting the advantages and disadvantages somewhere between the previous two cases.

The first and the second approach do not give an optimal solution. Since the third approach includes predictive control strategy, there is a need for additional optimization upon meteorological data. Using this approach, the battery will be filled from the grid only when its SOC is less than some predefined value (SOC minimum). The SOC minimum has to be less than SOC set point value. Modifying these parameters a trade – off between autonomy and efficiency is achieved.

B. Optimization

Optimization of the controller is based on the analysis and selection of optimal values of parameters relating to the third approach from previous discussions. In Fig. 7 from [8] the typical daily load and energy input variations in a stand-alone renewable energy system can be found. This diagram shows typical load (L), solar outputs (S) and wind outputs (W) for an average set of conditions. Battery SOC is also plotted on the same axes for the typical daily load variation. This diagram in particular shows the two days variations, when a day of low inputs is followed by a day of high inputs. In these cases the stand-by power supply would come in on-line (SB) to prevent battery from progressively discharge. This would result in charging the battery until it reaches SOC=100% or some other predetermined value. If now a day follows with high solar/wind inputs, the energy is lost, as the batteries are already full, which result in "spilt" (cross-hatched area).

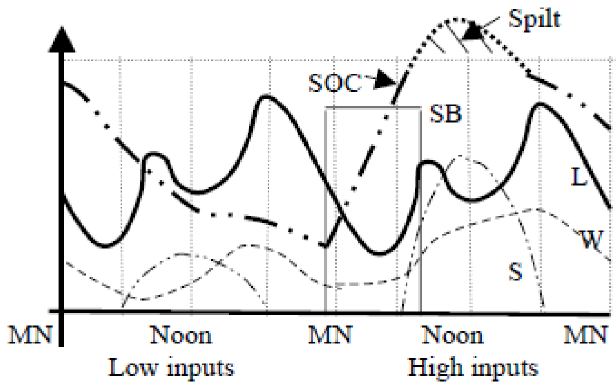

Figure 7 Daily energy flows

In this case, a stand-alone renewable energy system was analyzed. It implies system with external power supply without grid connection. Amount of renewable energy which is surplus for that day is predicted using forecast daily load, solar and wind energy production. This energy was subtracted from 100% SOC to determine a recommended cut-out SOC. Now, external power supply was disconnected when this modified cut-out point is reached, since the goal is to minimize waste of renewable energy.

The same model was used to simulate the behavior of the grid connected system. In this case, it will be assumed that grid supplies whatever energy is required from both storage and load. The grid will be able to absorb any potential spilt of energy, when the battery is full. The objective now becomes not an exercise to minimize import, but rather to create a smooth, uniform daily consumption from the grid, to enable optimum use of grid capacity.

6. CONCLUSION

In this paper preliminary considerations concerning RET simulator is presented. The simulator will serve decision support on investments related to RET deployment in the building domain. Using iterative approach, most appropriate renewable energy architecture and energy units were selected. Control logic inside simulator was built upon meteorological forecast data, the daily load on power supply network, the consumption of certain locations and SOC.

Based on selection of system architecture and optimized control logic, the simulator will be able to send appropriate set points to the controller. A compromise must be reached in order to achieve satisfactory trade-off between energy-efficiency and cost-benefit.

ACKNOWLEDGEMENTS

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